THE ASTROPHYSICAL JOURNAL, 235:57–62, 1980 January 1

OBSERVATIONS OF INTERSTELLAR H_2O EMISSION AT 183 GIGAHERTZ

J. W. WATERS, J. J. GUSTINCIC,[1] R. K. KAKAR, T. B. H. KUIPER, H. K. ROSCOE,[2] AND P. N. SWANSON
Jet Propulsion Laboratory, California Institute of Technology
E. N. RODRIGUEZ KUIPER
Ball Aerospace Systems Division, Western Laboratories, Gardena, California
AND
A. R. KERR AND P. THADDEUS
Goddard Institute for Space Studies, New York
Received 1978 March 27; accepted 1979 July 19

ABSTRACT

Line emission at 183 GHz by the 3_{13}–2_{20} rotational transition of water vapor has been detected from the Orion Nebula with the NASA Kuiper Airborne Observatory 91 cm telescope. The peak antenna temperature of the line is 15 K, its LSR velocity is 8 km s^{-1}, and its width is 15 km s^{-1}. The velocity profile has characteristics similar to those for CO: a narrow ($\sim$4 km s^{-1}) "spike" centered at 9.5 km s^{-1} and a broad "plateau" with flaring wings centered at $\sim$8 km s^{-1}. Our 7'.5 antenna beam did not resolve the source. The 183 GHz H_2O plateau emission appears enhanced above that expected for thermal excitation if it originates from the no greater than 1' region characteristic of plateau emission from all other observed molecules. The spike emission is consistent with an optically thick source of the approximate size of the well-known molecular ridge in Orion having the H_2O in thermal equilibrium at $T \approx 50$ K. If this is the case, then the H_2O column density giving rise to the spike is $N_{H_2O} \geq 3 \times 10^{17}$ cm^{-2}. An excitation calculation implies $N_{H_2O} \approx 10^{18}$ cm^{-2} for a source the size of the molecular ridge. These results imply that H_2O is one of the more abundant species in the Orion Molecular Cloud.

H_2O emission at 183 GHz was not detected in Sgr A, Sgr B2, W3, W43, W49, W51, DR 21, NGC 1333, NGC 7027, GL 2591, or the ρ Oph cloud; it may have been detected in M17.

Subject headings: infrared: sources — interstellar: abundances — interstellar: molecules — line identifications — nebulae: Orion Nebula — radio sources: lines

I. DEDICATION

This paper is dedicated to the memory of Jacob J. Gustincic, who was killed in a commercial jetliner crash on 1978 September 25. Dr. Gustincic's pioneering efforts in millimeter and submillimeter receiver development helped make possible the measurements reported here.

II. INTRODUCTION

The abundance and distribution of water vapor in interstellar molecular clouds are almost entirely unknown because its rotational emission lines (mainly in the infrared) are highly absorbed by water vapor in the terrestrial atmosphere. A notable exception, the 22 GHz 6_{16}–5_{23} transition, is fairly transparent in the atmosphere but is observed astronomically only as maser point sources; it has never been found in more extended objects or provided H_2O abundance data.

As part of NASA's advanced sensor development and stratospheric research programs, we constructed a portable spectral line receiver capable of observing the 183 GHz H_2O 3_{13}–2_{20} transition. From sea level at mid-latitude the atmospheric zenith optical depth in the center of the 183 GHz line is $\sim$20 (Waters 1976); from the lower stratosphere, however, it is only about 0.2, so it is easy in principle to observe the cosmic line from a high flying aircraft. We report here an aircraft search for water vapor at 183 GHz in a number of molecular clouds and its detection in the Orion Nebula. An estimate of the H_2O abundance in Orion is obtained. Phillips *et al.* (1978) have also recently reported detection of the corresponding $H_2{}^{18}O$ transition at 203 GHz in the Orion Nebula and DR 21(OH); they also obtained an estimate for the abundance of H_2O in Orion.

III. OBSERVATIONS

Observations were made on 1976 October 14 and 15 and 1977 July 20 and 22, October 26, and December 13 and 15 with the Kuiper Airborne Observatory (KAO), a 91 cm Cassegrain telescope on a modified C-141 aircraft operated by the NASA Ames Research Center. This instrument, intended primarily for infrared astronomy, is normally used at night to permit computer-controlled video guiding by a tracking camera which observes field stars. It is generally possible to point to within 10".

[1] Consulting engineer.
[2] US National Research Council Resident Research Associate.

Our receiver is a double-sideband superheterodyne radiometer with an intermediate frequency of 1420 MHz. The signal and local oscillator are combined quasi-optically (Gustincic 1976) to reduce waveguide losses. The mixer uses a GaAs Schottky-barrier diode, fabricated by R. J. Mattauch at the University of Virginia, which is mounted on a quartz microstrip (Kerr, Mattauch, and Grange 1977). The lowest double-sideband system temperature attained at 183 GHz with this receiver during the flights was ~2000 K. In the initial 1976 October flights the system temperature was approximately 3 times higher because of low local oscillator power.

Optical alignment of the receiver and telescope with the tracking camera was established on the ground by positioning Polaris in the center of the focal plane feed aperture at which the receiver is mounted. After the receiver is mounted, a visibly opaque lens covers this aperture and forms the pressure seal to the telescope cavity; this prevents focal plane alignment checks while the instrument is airborne. During airborne observations the edge of the Moon was initially used to check the alignment, which is known to change by ~3′ when the telescope cavity cools to stratospheric temperatures. After an unexplained shift of ~7′ during a flight on 1977 October 22 the KAO staff installed a beam-diverter mirror to provide an alignment check that did not require Moon observations. The mirror is inserted into the optical path of the telescope upon command and diverts the image to a video camera for a visible pointing check. This method was used for our subsequent observations; experience indicates that it is accurate and reliable to a small fraction of our 7.′5 beam.

The receiver optics were designed for a −18 dB illumination taper on the secondary, and scans across the edge of the Moon were consistent with the diffraction-limited half-power beamwidth of 7.′5 expected from this design. The beam efficiency at 183 GHz was determined in flight to be 0.5 by measuring the apparent Moon brightness relative to internal calibration targets at 77 and 300 K and correcting for atmospheric absorption. The atmospheric zenith transmissivity from a 12.5 km altitude was determined to be 0.85 at the center of the atmospheric line by separate measurements of its emission. The brightness temperature of the observed sunlit face of the Moon at 183 GHz was assumed to be 315 K (Muhleman 1972). Our antenna temperature calibration using these data is estimated to be accurate to within approximately 30%.

Observations were performed using a beam-switching technique implemented by nodding the telescope secondary mirror at 4 Hz. The beam was switched in azimuth between the source and a reference position 15′ away, which canceled the stratospheric H_2O emission. The reference position was changed from one side of the source to the other on alternate integrations; each integration lasted approximately 5 minutes. Spectral analysis was performed in parallel by a filter bank and a digital Fourier transform spectrometer. The filter bank had 13 central filters 3 MHz wide and two edge filters 32 MHz wide for a total bandwidth of 96 MHz. The Fourier transform spectrometer, with 256 channels each 39 kHz wide, had a total bandwidth of 10 MHz located in the center of the band of the filter bank. System control and calibrations were done by a desk top computer which is part of the receiver system. Calibrated spectra were then passed to the KAO computer system, which stored the data on disk and was used for further in-flight data reduction.

IV. RESULTS

We surveyed a set of the major H II/molecular complexes in the Galaxy and the planetary nebula NGC 7027. Table 1 summarizes the results.

An emission feature, shown in Figure 1, was de-

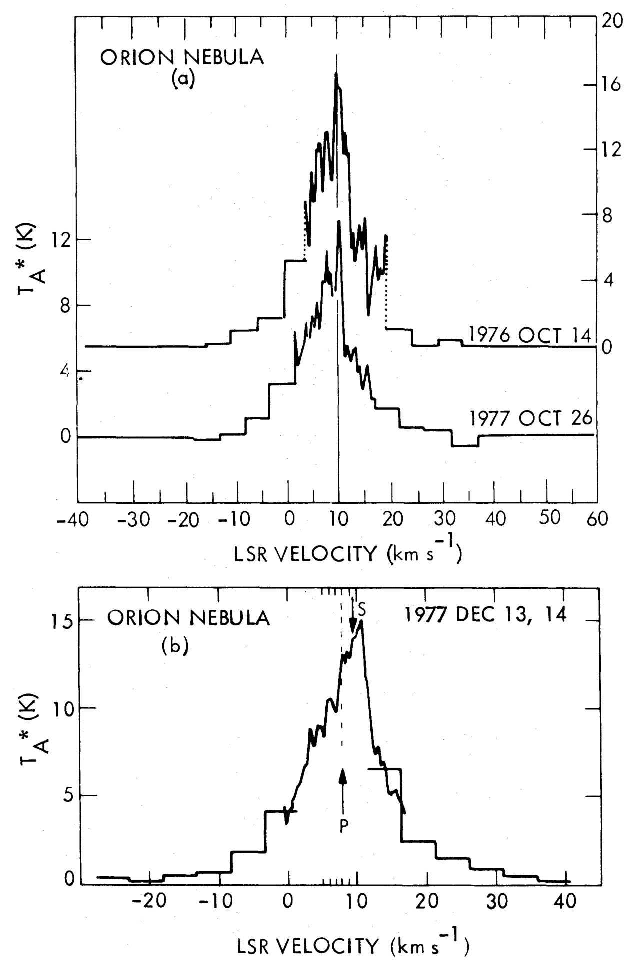

FIG. 1.—The 3_{13}–2_{20} transition of H_2O observed in the direction of the Orion Nebula. The apparent brightness temperature, T_A^*, is the measured antenna temperature corrected for beam efficiency and atmospheric absorption. The velocity is given with respect to the local standard of rest and a rest frequency of 183.31009 GHz. (*a*) Spectra observed on 1976 October 14 (*right temperature scale*) and 1977 October 26 (*left temperature scale*). (*b*) Spectrum observed on 1977 December 13 and 14 with two local oscillator settings separated by 3.4 MHz and averaged; the centers of the "spike" (*S*) and "plateau" (*P*) spectral features are indicated.

TABLE 1

SUMMARY OF 183 GHz H_2O OBSERVATIONS

Source	α(1950.0)	δ(1950.0)	LSR Velocity Range Searched (km s^{-1})	T_A* (K)[a]	V_{LSR} (km s^{-1})	ΔV (km s^{-1})	Date of Observation
W3	$2^h21^m53^s$	+61°52′21″	−74 to −9	< 0.9	...	...	1977 Dec 13
W3(OH)	2 23 17	+61 39 00	−80 to +5	< 0.7	...	...	1976 Oct 14, 15; 1977 Dec 15
NGC 1333	3 25 56	+31 10 10	−25 to +40	< 2.5	...	...	1976 Oct 14
Ori A (center)	5 32 47	−5 24 24	−25 to +45	14 ± 1[b]	8	15	1976 Oct 14, 15; 1977 Oct 26, Dec 13, 15
Ori A (7′N)	5 32 47	−5 17 24	−25 to +45	< 2	...	...	1976 Oct 14
Ori A (4′N)	5 32 47	−5 20 24	−25 to +45	3.8 ± 1.4	8	15	1977 Dec 15
Ori A (4′S)	5 32 47	−5 28 24	−25 to +45	7.7 ± 1.6	8	10	1977 Dec 15
Ori A (7′S)	5 32 47	−5 31 24	−25 to +45	< 2	...	...	1976 Oct 14
Ori A (4′E)	5 33 03	−5 24 24	−25 to +45	6.4 ± 2.8	8	15	1977 Dec 15
Ori A (4′W)	5 32 31	−5 24 24	−25 to +45	6.6 ± 2.8	8	13	1977 Dec 15
ρ Oph	16 23 00	−24 18 00	−29 to +36	< 1.0	...	...	1977 July 22
Sgr A	17 42 28	−28 58 30	+23 to +88	< 0.8	...	...	1977 July 20
Sgr B2	17 44 11	−28 22 30	+28 to +93	< 0.9	...	...	1977 July 20
M17	18 17 26.5	−16 14 54	−13 to +52	(1.0 ± 0.5)	(20)	(5)	1977 July 22
W43	18 45 00	−2 00 00	+66 to +131	< 1.8	...	...	1977 July 22
W49	19 07 54	+9 00 40	−18 to +47	< 0.9	...	...	1977 July 20
W51	19 21 23	+14 24 00	+37 to +102	< 1.0	...	...	1977 July 22
GL 2591	20 27 36	+40 01 16	−37 to +28	< 2.6	...	...	1977 July 22
DR 21	20 37 13	+42 08 51	−32 to +33	< 1.1	...	...	1976 Oct 14; 1977 July 20; 1977 Dec 15
NGC 7027	21 05 09	+42 02 03	−7 to +58	< 3.7	...	...	1977 Dec 13

[a] The errors quoted are 2 σ. The upper limits are 3 σ with a 3 MHz bandwidth.

[b] For Orion, the T_A* refer to the "spike" between 10 and 11 km s^{-1}. The V_{LSR} and ΔV refer to the entire line.

tected in the direction of the Kleinmann-Low (KL) nebula in Orion. The ordinate in Figure 1, the apparent brightness temperature T_A*, is the measured antenna temperature corrected for the beam efficiency and atmospheric absorption; the abscissa, radial velocity relative to the local standard of rest (LSR), is based on the measured value of 183.31009 GHz for the rest frequency of the H_2O 3_{13}–2_{20} transition (De Lucia, Helminger, and Kirchhoff 1974). The intensity, radial velocity, and width of the emission line measured in the KL nebula and adjacent positions are given in Table 1. The line is centered at an LSR velocity of ~8 km s^{-1} and has a width of ~15 km s^{-1}. The line is definitely astronomical in origin since it is seen only in the direction of the Orion Nebula and since its central frequency relative to the terrestrial line changed from −5 km s^{-1} in October to +17 km s^{-1} in December, as expected for a line originating in Orion at an LSR velocity of 10 km s^{-1}.

A five-point map was made of the Orion emission. The measured convolution of the emission and antenna beam had half-power full widths of 7.′5 with uncertainties of ~1′. This implies that the 183 GHz Orion source is substantially smaller than our beamwidth.

V. DISCUSSION

a) *Orion Nebula*

The 183 GHz emission profile appears to contain two features: (i) a narrow "spike" with a width of ~4 km s^{-1} centered at ~9.5 km s^{-1} and (ii) a broader "plateau" with extended wings centered at ~8 km s^{-1}. This differs greatly from the Orion 22 GHz H_2O maser emission, which consists of a number of sharp, intense features ranging from −90 to +80 km s^{-1} (e.g., Genzel and Downes 1977).

It would seem likely that the 183 GHz plateau emission originates from the same region as the plateau emission of all other observed molecules, a region known to be smaller than 1′ (Phillips *et al.* 1977). At a velocity of ±10 km s^{-1} with respect to the center of the 183 GHz H_2O plateau emission, the corrected antenna temperature is ~3 K. Our beam size of 7.′5 then implies a plateau brightness temperature of at least 170 K under the assumption that the source size is no larger than that of the other observed molecules. If this assumption is correct, the 183 GHz plateau emission is enhanced above that expected for thermal excitation of the H_2O. We will not further discuss the plateau emission in this paper.

The spike component in all molecular emission from Orion is strongly concentrated toward a region known as the "molecular ridge," which varies in size from $\alpha \times \delta = 4' \times 9'$ for the 115 GHz line in CO (Liszt *et al.* 1974) to $\alpha \times \delta = 2' \times 5'$ in formaldehyde and 1 mm continuum emission (Harvey *et al.* 1974). The observed 183 GHz H_2O spike emission is consistent with an optically thick source of this size having a brightness temperature equal to the kinetic temperature of the gas and dust in the ridge: ~80 K near the center, tapering off to ~50 K at the edges (Werner *et al.* 1976; Ulich and Haas 1976; Linke and Wannier 1974).

We will first estimate the H_2O column density from the spike emission by assuming thermal distribution of the H_2O rotational states. The optical depth τ can be written

$$\tau = N_{H_2O} f_u \frac{c^3 A}{8\pi\nu^3 \Delta v}\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right], \qquad (1)$$

where N_{H_2O} is the H_2O column density, f_u is the fraction of H_2O molecules in the upper 3_{13} state of the 183 GHz transition, $A = 3.6 \times 10^{-6}\ s^{-1}$ is the spontaneous emission coefficient, $\nu = 183.3$ GHz, $\Delta v = 4\ km\ s^{-1}$ is the observed spike line width, h is Planck's constant, k is Boltzmann's constant, c is the speed of light, and T is temperature. Under the assumption that the H_2O states have a thermal distribution, the fraction of molecules in the 3_{13} state is

$$f_u = \frac{g_u \exp(-hcE_u/kT)}{Q_r}, \qquad (2)$$

where $g_u = 7$ is the degeneracy of the state, $E_u = 142.2\ cm^{-1}$ is its energy, and Q_r is the rotational partition function. (There is negligible population of the excited vibrational and electronic states for the temperatures expected in the KL nebula.) Figure 2 gives τ/N_{H_2O} as a function of temperature calculated from the above expressions, with the rotational partition function evaluated for $T \leq 40$ K from a direct state sum and for $T \geq 40$ K from the asymptotic expansion which includes all "correction" terms of first order in the principal moments of inertia and their cross products (Stripp and Kirkwood 1951). (At $T = 40$ K the partition function evaluated by the two methods agrees to within 1%.)

An upper limit on the brightness temperature T_B of the observed emission is $T_B \leq T\tau$; this places a lower limit on the H_2O column density of

$$N_{H_2O} \geq \frac{T_B}{T}\frac{N_{H_2O}}{\tau}, \qquad (3)$$

where the equality holds for $\tau \ll 1$. At this point in the interpretation assumptions of the spike optical depth and of the source size must be introduced. If the spike is optically thick, then the entire 15 K measured antenna temperature originates from it; if it is optically thin, then only $\sim$5 K originates from the spike, the remaining $\sim$10 K arising from the plateau. For a source the size of the molecular ridge ($\sim$4′) correction for beam dilution then gives $T_B \approx 20$ K if the spike is optically thin and $T_B \approx 50$ K if it is optically thick. From equation (3) and the values of τ/N_{H_2O} in Figure 2 we obtain (*a*) $N_{H_2O} \approx 1.5 \times 10^{17}\ cm^{-2}$ for an optically thin spike and $T = 50$ K and (*b*) $N_{H_2O} \geq 3 \times 10^{17}\ cm^{-2}$ for an optically thick spike.

We have also used the same model as Phillips *et al.* (1978) to calculate the 183 GHz H_2O emission from the molecular ridge but with a radiation field of the form proposed by Werner *et al.* (1976) modified to have a dust temperature of 50 K so as to achieve a better fit to the observed IR flux from the extended dust cloud (Harper 1974; Houck, Schaack, and Reed 1974; Gezari *et al.* 1974; Brandshaft, McLaren, and Werner 1975; Westbrook *et al.* 1976). Our calculation assumed no dilution of the radiation field (corresponding to $f = 1$ in the notation of Phillips *et al.* 1978). An H_2 density of $10^5\ cm^{-3}$ (Evans *et al.* 1975) and He–H_2O collision cross sections computed by Green (1980) for kinetic temperatures of 40 and 60 K were used. (Cross sections for 50 K were not available.) Figure 3 shows the results of these calculations. These results indicate that (for a 4 km s^{-1} line width and kinetic temperatures of 40–60 K) the brightness tem-

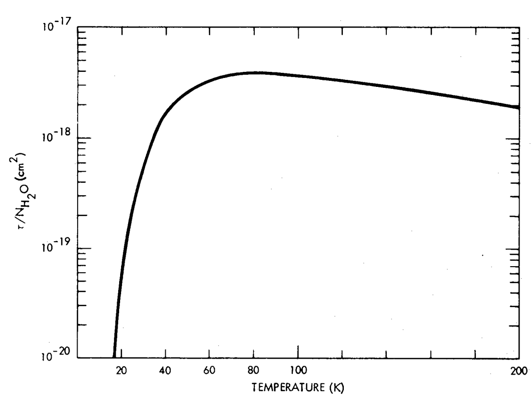

FIG. 2.—Opacity of the 183 GHz H_2O transition per unit column density for water in thermal equilibrium.

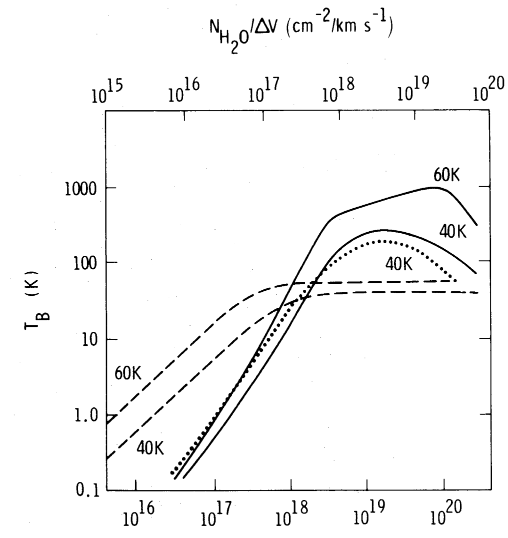

FIG. 3.—Brightness temperature as a function of water column density for a line width of 4 km s^{-1} as observed for the 183 GHz spike. (The upper scale gives $N_{H_2O}/\Delta v$, which requires no assumption about line width.) The solid curves represent the results using the same model as Phillips *et al.* (1978) but with parameters as given in the text. The dotted curve gives the results for gas at 40 K with reduced escape probability. The dashed curves are for water in thermal equilibrium.

perature of the 183 GHz emission is less than would be expected for a thermal source if $N_{H_2O} < \sim 10^{18}$ cm^{-2} and is more if $N_{H_2O} > \sim 10^{18}$ cm^{-2}. To estimate the sensitivity of this result to the form assumed for the escape probability, we also performed the calculation for 40 K using a reduced escape probability obtained by increasing the opacity threefold, which is appropriate to an expanding plane-parallel geometry (Sobolev 1957), and obtained the dotted curve in Figure 3. As expected, higher excitation is maintained at lower column densities because the photons cannot escape as easily. At higher column densities where the optical depth is large the reduced escape probability gives the excited molecules a greater opportunity to collide with hydrogen molecules, which tends to thermalize the population distribution.

For a 4′ source and optically thin spike our measurements indicate $T_B \approx 20$ K as discussed above. The excitation calculation results shown in Figure 3 then imply $N_{H_2O} \approx 8 \times 10^{17}$ cm^{-2}. For an optically thick spike $T_B \approx 50$ K, and the calculation implies $N_{H_2O} \approx 1.2 \times 10^{18}$ cm^{-2}. (Liebe and Dillon 1969 measured the H_2–H_2O collision cross section to be ~ 3 times larger than the He–H_2O collision cross section for the 22 GHz H_2O transition. If this also applies for the H_2O transitions involved in the 183 GHz line excitation, then our calculations using the larger cross sections indicate that the above estimate of N_{H_2O} needs to be revised downward by $\sim 30\%$.)

For a source size of $\sim 1'.3$, as determined by Phillips *et al.* (1978) for the corresponding $H_2{}^{18}O$ line in Orion, correction for beam dilution gives $T_B \approx 170$ K for an optically thin and $T_B \approx 500$ K for an optically thick spike. For these cases we performed excitation calculations as described above but with parameters more appropriate for the smaller source: a kinetic temperature of 80 K, an H_2 density of 10^6 cm^{-3}, and the radiation field given by Werner *et al.* (1976). For $T_B \approx 170$ K (optically thin spike) these calculations give $N_{H_2O} \approx 10^{17}$ cm^{-2}, and for $T_B \approx 500$ K (optically thick spike) they yield $N_{H_2O} \approx 6 \times 10^{17}$ cm^{-2}. From their $H_2{}^{18}O$ observations and assumed terrestrial [^{16}O]/[^{18}O] ratio Phillips *et al.* (1978) obtain 8 cm^{-3} for the H_2O number density in Orion, which corresponds to $N_{H_2O} \approx 5 \times 10^{18}$ cm^{-2} for a $1'.3$ source at 460 pc. The difference between our result for N_{H_2O} and that of Phillips *et al.* is due to differences in the assumed radiation field and line width; Phillips *et al.*, of course, had to also assume a value for [^{16}O]/[^{18}O].

Clearly, a valid H_2O abundance from the 183 GHz data must await determination of the source size. However, the results obtained here suggest that H_2O is probably one of the more abundant species in the Orion Molecular Cloud, having a column density in the range 10^{17}–10^{18} cm^{-2}. The column density of CO, the most abundant molecule observed with radio techniques, is about 2×10^{19} cm^{-2} (Liszt *et al.* 1974), and, e.g., the column densities of CH_3OH, CS, HCN, and H_2CO are in the range 2×10^{14} to 2×10^{15} cm^{-2} (Liszt *et al.* 1974; Gottlieb *et al.* 1975; Evans *et al.* 1975). The column density of H_2, presumably the dominant molecule, has been estimated from a number of investigations to be of the order of 2×10^{23} cm^{-2} (e.g., Evans *et al.* 1975). Our data and interpretation then imply [H_2O]/[H_2] $\approx 5 \times 10^{-7}$ to 5×10^{-6} and [H_2O]/[CO] $\approx 5 \times 10^{-3}$ to 5×10^{-2}. This is evidently consistent with the prediction of ion-molecule chemistry that [H_2O]/[CO] < 0.16 (Snyder, Watson, and Hollis 1977).

It is of interest to note that the column density of H_2S in the KL nebula is $\sim 4 \times 10^{13}$ cm^{-2} (Thaddeus *et al.* 1972), which, with our 183 GHz interpretation, implies that [H_2O]/[H_2S] $\approx 3 \times 10^2$ to 3×10^3, more than 40 times larger than the cosmic [O]/[S] ratio (Allen 1964).

One final comparison with other measurements is pertinent. Turner *et al.* (1975) have detected HDO at 80 GHz and tentatively concluded that [HDO]/[H_2] $\approx 10^{-8}$ in the KL nebula. (The observed HDO line profile is very similar to that for our 183 GHz H_2O line.) With this value and assuming that the relative abundance and degree of deuteration of water are the same in the ridge as they are in the IR nebula, our results suggest [HDO]/[H_2O] $\approx 2 \times 10^{-3}$ to 2×10^{-2}. Since the [D]/[H] ratio in the diffuse interstellar gas is known from *Copernicus* observations to be about 1.8×10^{-5} (York and Rogerson 1976), the difference of two to three orders of magnitude leads us, in spite of the crudeness of the assumptions, to suspect that H_2O, like many interstellar molecules (Rodriguez Kuiper, Zuckerman, and Kuiper 1978; Turner and Zuckerman 1978), concentrates deuterium.

b) *Negative Results*

Our negative results are consistent with the H_2O rotational levels having a semblance of normal excitation. For temperatures below 40 K the opacity per unit column density drops sharply as shown in Figure 2. We have collected in Table 2 the 115 GHz ^{12}CO brightness temperatures and distances for the sources in Table 1. The only source whose temperature suggests that the 183 GHz transition may have a significant optical depth is M17. M17 is at a distance of ~ 2 kpc so that if the source were similar in size to the Orion source, the M17 signal would be down by ~ 20 times owing to beam dilution. Our single observation of M17 does suggest a feature of this amplitude at about the 4 σ confidence level, but more observations will be required to substantiate it.

We are grateful for helpful suggestions and criticisms by N. Evans, P. Goldsmith, W. Huntress, M. Litvak, T. Phillips, H. Pickett, and B. Zuckerman. We thank R. Biswell, J. Grange, J. Hardy, and W. Ricketts for assistance in constructing the receiver; R. Mattauch for producing the mixer diodes; C. Gillespie, J. McClenahan, and the staff of the Kuiper Airborne Observatory for assistance with the installation of the receiver and beam diverter on the telescope and with performance of the observations; T. Mathieson and other members of the KAO computer staff for help in developing the data reduction

TABLE 2

BRIGHTNESS TEMPERATURES AND DISTANCES OF OBSERVED ^{12}CO SOURCES[a]

Source	T_A (K)	Distance (kpc)	Reference for T_A	Reference for Distance
W3	(10.4)[b]	3	Wilson *et al.* 1974	Reifenstein *et al.* 1970
W3(OH)	(6.6)[b]	3	Wilson *et al.* 1974	Reifenstein *et al.* 1970
NGC 1333	20	0.5	Lada *et al.* 1974	Strom *et al.* 1974
Ori A (KL)	60	0.46	Ulich and Haas 1976	Allen 1964
ρ Oph	27.5	0.16	Encrenaz 1974	Encrenaz 1974
Sgr A	20–40	10	Liszt *et al.* 1975	"Conventional" distance to galactic center
Sgr B2	16	10	Wannier *et al.* 1976	
M17	39.5	2	Ulich and Haas 1976	Reifenstein *et al.* 1970
W43	(9.5)[b]	8.5	Wilson *et al.* 1974	Reifenstein *et al.* 1970
W49	25	14	Mufson and Liszt 1977	Reifenstein *et al.* 1970
W51	28.4	6.5	Ulich and Haas 1976	Reifenstein *et al.* 1970
GL 2591	11	1.5	Kuiper *et al.* 1979	Wendker and Baars 1974
DR 21	24	1.5	Wannier *et al.* 1976	Reifenstein *et al.* 1970
NGC 7027	1.8	1.8	Mufson *et al.* 1975	O'Dell 1962

[a] The temperatures given here are actually corrected antenna temperatures, which should be reasonable indicators of the brightness temperatures since all the sources were resolved except where noted.

[b] Observed with a 2′ beam and generally believed to be about a factor of 2 too small.

software; and R. Cofield for assistance in programming the numerical models. The research carried out at the Jet Propulsion Laboratory, California Institute of Technology, was sponsored by the National Aeronautics and Space Administration under contract NAS 7-100.

REFERENCES

Allen, C. W. 1964, *Astrophysical Quantities* (London: Athlone).
Brandshaft, D., McLaren, R. A., and Werner, M. W. 1975, *Ap. J.* (*Letters*), **199**, L115.
De Lucia, F. C., Helminger, P., and Kirchhoff, W. H. 1974, *J. Phys. Chem. Ref. Data*, **3**, 211.
Encrenaz, P. J. 1974, *Ap. J.* (*Letters*), **189**, L135.
Evans, N. J., II, Zuckerman, B., Sato, T., and Morris, G. 1975, *Ap. J.*, **199**, 383.
Genzel, R., and Downes, D. 1977, *Astr. Ap.*, **61**, 117.
Gezari, D. Y., Joyce, R. R., Righini, G., and Simon, M. 1974, *Ap. J.* (*Letters*), **191**, L33.
Gottlieb, C. A., Lada, C. J., Gottlieb, E. W., Lilley, A. E., and Litvak, M. M. 1975, *Ap. J.*, **202**, 655.
Green, S. 1980, *Ap. J. Suppl.*, **42**, in press.
Gustincic, J. J. 1976, in *Digest 2d Internat. Conf. Submillimeter Waves and Their Applications* (IEEE 76 CH 1152-8 MTT), p. 106.
Harper, D. A. 1974, *Ap. J.*, **192**, 557.
Harvey, P. M., *et al.* 1974, *Ap. J.* (*Letters*), **189**, L87.
Houck, J. R., Schaack, D. F., and Reed, R. A. 1974, *Ap. J.* (*Letters*), **193**, L139.
Kerr, A. R., Mattauch, R. J., and Grange, J. 1977, *IEEE Trans. Microwave Theory Tech.*, **25**, 399.
Kuiper, T. B. H., Rodriguez Kuiper, E. N., and Zuckerman, B. 1979, private communication.
Lada, C. J., Gottlieb, C. A., Litvak, M. M., and Lilley, A. E. 1974, *Ap. J.*, **194**, 609.
Liebe, H. J., and Dillon, T. A. 1969, *J. Chem. Phys.*, **50**, 727.
Linke, R. A., and Wannier, P. G. 1974, *Ap. J.* (*Letters*), **193**, L41.
Liszt, H. S., Sanders, R. H., and Burton, W. B. 1975, *Ap. J.*, **198**, 537.
Liszt, H. S., Wilson, R. W., Penzias, A. A., Jefferts, K. B., Wannier, P. G., and Solomon, P. M. 1974, *Ap. J.*, **190**, 557.
Mufson, S. L., and Liszt, H. S. 1977, *Ap. J.*, **212**, 664.
Mufson, S. L., Lyon, J., and Marionni, P. A. 1975, *Ap. J.* (*Letters*), **201**, L85.
Muhleman, D. O. 1972, *Progress in Astronautics and Aeronautics*, Vol. 28 (Cambridge: MIT Press), chap. 1b.
O'Dell, C. R. 1962, *Ap. J.*, **135**, 371.
Phillips, T. G., Huggins, P. J., Neugebauer, G., and Werner, M. W. 1977, *Ap. J.* (*Letters*), **217**, L161.
Phillips, T. G., Scoville, N. Z., Kwan, J., Huggins, P. J., and Wannier, P. G. 1978, *Ap. J.* (*Letters*), **222**, L59.
Reifenstein, E. C., III, Wilson, T. L., Burke, B. F., Mezger, P. G., and Altenhoff, W. J. 1970, *Astr. Ap.*, **4**, 357.
Rodriguez Kuiper, E. N., Zuckerman, B., and Kuiper, T. B. H. 1978, *Ap. J.* (*Letters*), **219**, L49.
Snyder, L. E., Watson, E. D., and Hollis, J. M. 1977, *Ap. J.*, **212**, 79.
Sobolev, V. V. 1957, *Soviet Astr.—AJ*, **1**, 678.
Stripp, K. F., and Kirkwood, J. G. 1951, *J. Chem. Phys.*, **19**, 1131.
Strom, S. E., Grasdalen, G. L., and Strom, K. M. 1974, *Ap. J.*, **191**, 111.
Thaddeus, P., Kutner, M. L., Penzias, A. A., Wilson, R. W., and Jefferts, K. B. 1972, *Ap. J.* (*Letters*), **176**, L73.
Turner, B., and Zuckerman, B. 1978, *Ap. J.* (*Letters*), **225**, L75.
Turner, B. E., Zuckerman, B., Fourikis, N., Morris, M., and Palmer, P. 1975, *Ap. J.* (*Letters*), **198**, L125.
Ulich, B. L., and Haas, R. W. 1976, *Ap. J. Suppl.*, **30**, 247.
Wannier, P. G., Penzias, A. A., Linke, R. A., and Wilson, R. W. 1976, *Ap. J.*, **204**, 26.
Waters, J. W. 1976, *Methods of Experimental Physics*, Vol. **12B** (New York: Academic Press), chap. 2.3.
Wendker, H. J., and Baars, J. W. M. 1974, *Astr. Ap.*, **33**, 157.
Werner, M. W., Gatley, I., Harper, D. A., Becklin, E. E., Loewenstein, R. F., Telesco, C. M., and Thronson, H. A. 1976, *Ap. J.*, **204**, 420.
Westbrook, W. E., Werner, M. W., Elias, J. H., Gezari, D. Y., Hauser, M. G., Lo, K. Y., and Neugebauer, G. 1976, *Ap. J.*, **209**, 94.
Wilson, W. J., Schwartz, P. R., Epstein, E. E., Johnson, W. A., Etcheverry, R. D., Mori, T. T., Berry, G. G., and Dyson, H. B. 1974, *Ap. J.*, **191**, 357.
York, D. G., and Rogerson, J. B., Jr. 1976, *Ap. J.*, **203**, 378.

R. K. KAKAR, T. B. H. KUIPER, E. N. RODRIGUEZ KUIPER, P. N. SWANSON, and J. W. WATERS: Jet Propulsion Laboratory, Pasadena, CA 91103

A. R. KERR and P. THADDEUS: Institute for Space Studies, 2880 Broadway, New York, NY 10025

H. K. ROSCOE: Department of Atmospheric Physics, Clarendon Laboratory, Parks Road, Oxford, England